RESEARCH MEMORANDUM

REYNOLDS NUMBER EFFECT ON AXIAL-FLOW

COMPRESSOR PERFORMANCE

By Lewis E. Wallner and William A. Fleming

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

An investigation has been conducted in the NACA Lewis altitude wind tunnel to study the effect of Reynolds number on the performance of an axial-flow compressor. The compressor was operated as an integral part of a turbojet engine over a range of pressure altitudes from approximately 17,000 to 50,000 feet and compressor-inlet Reynolds numbers from 60,300 to 219,500.

The results of this investigation showed that the decrease in compressor efficiency and corrected air flow with a reduction in pressure at each compressor Mach number was caused by the corresponding reduction in compressor-inlet Reynolds number. The rate of change of efficiency with Reynolds number was more pronounced at the lower Reynolds numbers. At a given compressor Mach number and pressure ratio, a decrease in Reynolds numbers from 205,000 to 65,000 lowered the compressor efficiency by approximately 0.05 and lowered the corrected air flow by 0.02 to 0.05 of the rated sea-level air flow. Performance obtained with two other compressors, each of different design, apparently correlated with compressor-inlet Reynolds number in a manner similar to that of the compressor used in this investigation.

INTRODUCTION

Investigations of axial-flow compressors over a wide range of simulated flight conditions have indicated that variations in compressor-inlet conditions affect the performance characteristics of some compressors. With such compressors, the effect of increasing the altitude is a reduction in the corrected air flow and the compressor efficiency at a given compressor Mach number and pressure ratio. Results obtained with several compressors of different design have shown that the inlet conditions at which the performance characteristics are affected and the magnitude of the variations in performance differ from one compressor to another. Compressor data previously obtained have indicated that the effect of increasing the inlet temperature or reducing the inlet pressure on compressor performance might be caused by changes in Reynolds number (reference 1 and proprietary NACA data). Investigation of the Reynolds number effect on airfoil drag coefficients (reference 2) has shown that reduction of the Reynolds number below the critical value increased the drag coefficient. As Reynolds number is reduced, the separation region shifts forward on the airfoil and increases the drag coefficient. If the airfoil is used in a cascade, this shift in the separation region will cause a decrease in cascade efficiency and may lower the corrected air flow.

An axial-flow-compressor type turbojet engine was investigated in the NACA Lewis altitude wind tunnel to determine whether variations of compressor performance with inlet conditions could be correlated with the attendant changes in Reynolds number. Variations of compressor performance with inlet conditions were obtained by operating the engine over a range of compressor-inlet Reynolds numbers at several compressor Mach numbers. At each compressor Mach number and Reynolds number, data were obtained at two inlet total pressures while the Reynolds number was maintained constant by changing the compressor-inlet temperature.

RANGE OF INVESTIGATION

Data were obtained over a range of pressure altitudes from approximately 17,000 to 50,000 feet at a constant compressor-inlet ram-pressure ratio of 1.03. At each condition, the compressor was operated over a range of compressor Mach numbers from 0.70 to the rated sea-level compressor Mach number of 0.89. For compressor Mach numbers below rated speed, the engine was operated with only two inlet total temperatures of approximately 460° and 600° R. Two corresponding inlet pressures were chosen at each compressor Mach number to give the same compressor-inlet Reynolds number for both inlet temperatures. At rated compressor Mach number, the engine was operated with an inlet temperature of approximately 507° R. The conditions at which data were obtained and the corresponding pressure altitudes are given in table I. At each condition, data were obtained at four compressor pressure ratios by varying the exhaust-nozzle area.

Compressor-inlet Reynolds number was calculated from the density of the air entering the first-stage rotor blades and the velocity relative to the first-stage rotor blades, as shown in the appendix. The Reynolds number of the first-stage rotor blades was selected so that the values presented could be directly compared with conventional airfoil Reynolds numbers and because the first stage, being subjected to the lowest values of Reynolds number in the compressor, would be most sensitive to changes in Reynolds number. As an aid in determining the Reynolds number of this compressor at inlet conditions other than those investigated, the relation between the Reynolds number index and the compressor-inlet Reynolds number is shown in the following table:

Compressor Mach number	$\dfrac{\text{Compressor-inlet Reynolds number}}{\text{Reynolds number index}}$
0.70	1.75×10^9
.76	1.89×10^9
.82	2.00×10^9
.89	2.14×10^9

The Reynolds number index varies linearly with Reynolds number and is defined as the ratio of inlet total pressure to the product of the square root of inlet total temperature and the viscosity of the air based on inlet total temperature.

INSTALLATION AND INSTRUMENTATION

An axial-flow-compressor type turbojet engine was installed in the test section of the altitude wind tunnel. With a variable-area exhaust nozzle installed on the engine, the compressor pressure ratio could be varied at each compressor Mach number and inlet condition. Dry air was introduced into the engine through a duct from the tunnel make-up air system. The air was throttled from approximately sea-level pressure to the desired pressure at the engine inlet, while the tunnel pressure was maintained to correspond to the desired altitude. Installation of refrigeration coils and electric heaters in the make-up air system made possible the variation of the engine-inlet temperature from about -20° to 150° F.

Instrumentation for measuring pressures and temperatures was installed at four stations in the compressor (fig. 1). The location and the details of the instrumentation for the engine inlet are shown in figure 2 and for the compressor outlet in figure 3. Four static wall orifices were installed 90° apart in a plane a short distance ahead of the compressor-inlet guide vanes, station 2.

RESULTS AND DISCUSSION

Results are presented showing the variation of compressor efficiency and corrected air flow with compressor pressure ratio for several Reynolds numbers. Data are presented in this form to show the results obtained by changing the inlet pressure while maintaining constant Reynolds number and Mach number. Air flow is expressed as the ratio of corrected air flow at the test condition to rated sea-level air flow. Results are also summarized to show the variation of compressor efficiency and fraction of rated sea-level air flow with Reynolds number at several compressor Mach numbers.

Compressor Efficiency

The variation of compressor efficiency with compressor pressure ratio at compressor Mach numbers from 0.70 to 0.82 is presented for a range of Reynolds numbers from 61,100 to 218,900 and compressor-inlet total pressures from approximately 250 to 1150 pounds per square foot in figures 4 to 6. Data for the same Reynolds number and two different inlet pressures interplotted reasonably well, although the data scatter became more pronounced as the pressure was lowered and the degree of accuracy of the measurements was correspondingly reduced. The results show that at a constant value of compressor Mach number a reduction in Reynolds number resulted in a steady decrease in compressor efficiency. Interplotting of the data indicated that decreasing the inlet pressure by approximately 30 percent at a given Reynolds number had no apparent effect on the compressor efficiency; also, regardless of whether the inlet pressure was raised or lowered, the compressor efficiency varied in the same direction as the Reynolds number. These effects are shown by typical values of compressor efficiency given in the following table for a compressor Mach number of 0.76 and a compressor pressure ratio of 3.9:

Compressor-inlet total pressure (lb/sq ft)	Reynolds number	Compressor efficiency
1143	208,500	0.845
807	207,300	.845
727	133,600	0.828
512	131,400	.828
450	82,200	0.815
318	83,700	.815
355	64,900	0.800
247	65,500	.800

The data presented in figures 4 to 6 are summarized in figure 7 to show the correlation of compressor efficiency with Reynolds number at constant compressor Mach numbers and pressure ratios. At each compressor Mach number, the compressor efficiency decreased as the Reynolds number was reduced; the decrease became more pronounced at the lower Reynolds numbers. At each compressor Mach

1161

number investigated, a decrease in Reynolds number from 205,000 to 135,000 reduced the efficiency by approximately 0.015. A corresponding reduction in Reynolds number from 135,000 to 65,000 lowered the efficiency by about 0.035.

Air Flow

A typical set of data is presented in figure 8 to show the relation between the compressor pressure ratio and the fraction of rated sea-level air flow for two approximate inlet pressures at compressor Mach numbers from 0.70 to 0.82 with an approximately constant Reynolds number at each compressor Mach number. Data for a compressor Mach number of 0.89 (rated compressor speed) are also included for only one inlet pressure. At each compressor Mach number and Reynolds number, data for the two different inlet pressures interplotted reasonably well. Similar interplotting of the data at other Reynolds numbers indicated that decreasing the inlet pressure by approximately 30 percent at a given Reynolds number had no effect on the corrected air flow.

The results are summarized in figure 9 to show the effect of Reynolds number on the relation between the fraction of rated sea-level air flow and compressor pressure ratio for a range of Reynolds numbers from 61,100 to 218,900 and compressor Mach numbers from 0.70 to 0.89. Regardless of how the inlet pressure was changed, at a given compressor pressure ratio the corrected air flow varied in the same direction as the Reynolds number at each compressor Mach number. As the Reynolds number was reduced, the curves of constant compressor Mach number shifted in the direction of reduced corrected air flow. The slope of the compressor Mach number curves was affected in such a manner that at the lower Reynolds numbers the corrected air flow decreased more rapidly as the compressor pressure ratio was raised.

Data presented in figure 9 are cross-plotted in figure 10 to show directly the reduction in the fraction of rated sea-level air flow as the Reynolds number was reduced at constant compressor Mach numbers and pressure ratios. At each compressor Mach number, the corrected air flow decreased as the Reynolds number was reduced; the decrease became more pronounced at the lower Reynolds numbers. At each compressor Mach number investigated, a decrease in Reynolds number from 205,000 to 135,000 reduced the corrected air flow by approximately 0.005 of the rated air flow. A corresponding reduction in Reynolds number from 135,000 to 65,000 lowered the corrected air flow by 0.015 to 0.045 of the rated air flow.

Comparison with Axial-Flow Compressors of Different Design

Compressor performance obtained with two other engines over a range of altitudes at approximately standard inlet conditions correlated with compressor-inlet Reynolds number in a manner similar to that of the performance for the compressor studied in this investigation (fig. 11). The other two axial-flow compressors, designated A and B and of different design than the subject compressor, were previously investigated in the Lewis altitude wind tunnel. Several fixed exhaust nozzles having different outlet areas were used on these two engines, making it possible to determine compressor performance at a given compressor pressure ratio and compressor Mach number at each altitude. A decrease in compressor efficiency and corrected air flow for compressors A and B accompanied a reduction in compressor-inlet Reynolds number in a manner similar to that of the compressor studied in this investigation; however, the magnitude of the compressor performance variation with Reynolds number differed among the three compressors.

1161

SUMMARY OF RESULTS

The following results were obtained from an investigation to determine the effect of compressor-inlet Reynolds number on the performance of an axial-flow compressor:

1. Changes in compressor efficiency and corrected air flow were found to correlate with changes in compressor-inlet Reynolds number. The rate of change of efficiency and corrected air flow with Reynolds number was more pronounced at the lower Reynolds numbers.

2. A decrease in compressor-inlet Reynolds number from 205,000 to 65,000 lowered the compressor efficiency by approximately 0.05 at each compressor Mach number investigated.

3. At a given compressor pressure ratio, a decrease in Reynolds number from 205,000 to 65,000 lowered the corrected air flow by 0.02 to 0.05 of the rated sea-level air flow.

4. Performance obtained with two other compressors, each of different design, correlated with compressor-inlet Reynolds number in a manner similar to that of the performance for the compressor studied in this investigation.

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APPENDIX - METHODS OF CALCULATION

Symbols

The symbols used in this report are defined as follows:

A	area, sq ft
c	chord length of first-stage rotor blade measured midway between blade root and tip, ft
c_p	specific heat at constant pressure, Btu/(lb)(°R)
D	compressor-rotor diameter, ft
g	acceleration due to gravity, 32.17 ft/sec^2
J	mechanical equivalent of heat, 778 ft-lb/Btu
M_c	compressor-tip Mach number
N	compressor speed, rpm
n	polytropic exponent
P	total pressure, lb/sq ft absolute
p	static pressure, lb/sq ft absolute
R	universal gas constant, 53.4 ft-lb/(lb)(°R)
Re	compressor-inlet Reynolds number
T	total temperature, °R
T_i	indicated temperature, °R
ΔT_c	total-temperature rise across compressor, °R
$\Delta T_{c,ad}$	adiabatic total-temperature rise across compressor, °R
t	static temperature, °R
U	tangential velocity of first-stage rotor blade measured at mean blade radius, ft/sec
V	velocity, ft/sec

W air flow, lb/sec

γ ratio of specific heats at constant pressure to specific heats at constant volume

η efficiency

θ effective turning angle of inlet guide vanes, deg

μ viscosity of air, lb-sec/sq ft

ρ density of air, slugs/cu ft

Subscripts:

1 engine inlet

2 compressor inlet

3 inlet to first rotor stage

4 compressor outlet behind straightening vanes

a axial

c compressor

p polytropic

r relative to rotor blades

Calculations

Temperature. - Total temperature was calculated from the expression

$$T = \frac{T_i\left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}}}{1 + 0.85\left[\left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{1}$$

where 0.85 is the thermocouple impact-recovery factor.

Air flow. - The air flow through the compressor was obtained from measurements at the engine inlet, station 1, by the following relation:

$$W = p_1 A_1 \sqrt{\frac{2\gamma g}{(\gamma-1)RT_1}\left(\frac{P_1}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\left[\left(\frac{P_1}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \tag{2}$$

Compressor efficiency. - Compressor efficiency is defined as the ratio of adiabatic enthalpy rise of the air across the compressor to the actual enthalpy rise and may be expressed by the following relation:

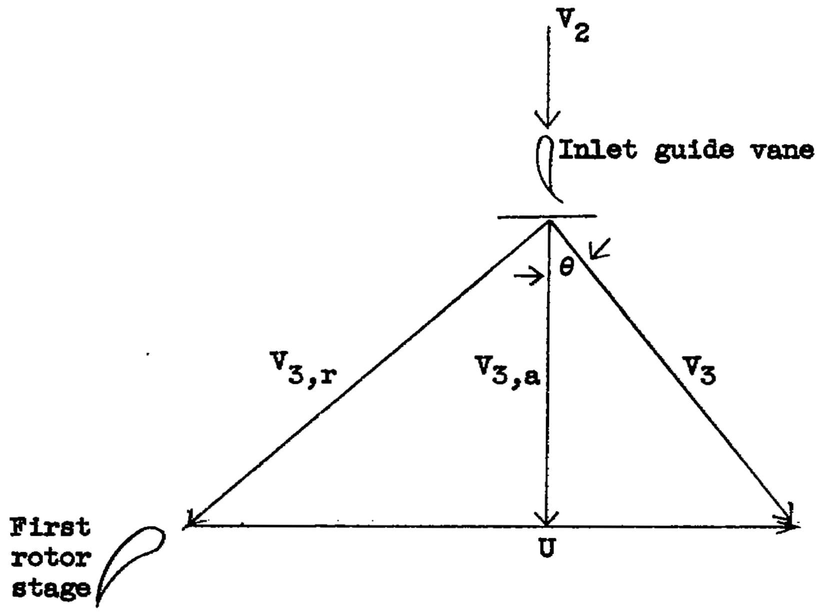
$$\eta_c = \frac{W\, c_p \Delta T_{c,ad}}{W\, c_p \Delta T_c} = \frac{\left(\frac{P_4}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\frac{T_4}{T_1} - 1} \tag{3}$$

The ratio of specific heats γ was based on the average temperature through the compressor $(T_1+T_4)/2$.

Compressor Mach number. - Compressor Mach number is defined as the tip speed of the rotor divided by the stagnation speed of sound at the compressor inlet.

$$M_c = \frac{\pi DN}{60\sqrt{\gamma g R T_1}} \tag{4}$$

Reynolds number. - The velocity diagram for the first compressor stage is



Because the area at station 2 was equal to the area at the entrance of the compressor-inlet guide vanes, conditions at the two stations were assumed equal. The axial velocity at the entrance to the inlet guide vanes V_2 was calculated from the static pressure and the static temperature at station 2 and the air flow.

$$V_2 = \frac{WRt_2}{p_2 A_2} \tag{5}$$

The total temperature and pressure at stations 1 and 2 were assumed equal and t_2 was obtained from the relation

$$t_2 = T_1\left(\frac{p_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \tag{6}$$

The average effective turning angle of the inlet guide vanes varies from 23° at the hub to 31° at the outer casing. An average turning angle of 27° was used for the calculations. The annular area at the exit of the guide vanes A_3 was equal to the area at station 2 (fig. 1). In order to calculate the Reynolds number relative to

1161

the first-stage rotor, it is first necessary to determine the axial velocity and the static temperature at the exit of the inlet guide vanes. The static temperature can be expressed as

$$t_3 = T_2 - \frac{V_3^2}{2Jgc_p} \tag{7}$$

$$t_3 = T_2 - \frac{V_{3,a}^2}{2Jgc_p \cos^2 \theta} \tag{8}$$

From the continuity equation

$$\rho_2 A_2 V_2 = \rho_3 A_3 V_{3,a} \tag{9}$$

and because $A_2 = A_3$

$$V_{3,a} = \frac{\rho_2}{\rho_3} V_2 \tag{10}$$

The density ratio across the inlet guide vanes may be expressed in terms of the static temperature ratio as

$$\frac{\rho_2}{\rho_3} = \left(\frac{t_2}{t_3}\right)^{\frac{1}{n-1}} \tag{11}$$

Because the flow can be considered adiabatic but not isentropic, the polytropic exponents must be calculated. A polytropic efficiency of 0.90 was assumed for the expansion through the inlet guide vanes and the exponent was calculated from the following equation:

$$\eta_p = \frac{\gamma}{\gamma-1} \frac{n-1}{n} \tag{12}$$

Combining equations (10) and (11) gives the following expression, which has only $V_{3,a}$ and t_3 as unknowns:

$$V_{3,a} = V_2\left(\frac{t_2}{t_3}\right)^{\frac{1}{n-1}} \tag{13}$$

The values of $V_{3,a}$ and t_3 were then obtained from a solution of equations (8) and (13) by a series of approximations. The density of the air leaving the inlet guide vanes was then calculated from equation (11). The viscosity μ_3 was determined from t_3.

Velocity of the air relative to the first-stage rotor blades was calculated as

$$V_{3,r} = \sqrt{{V_{3,a}}^2 + (U - V_{3,a} \tan \theta)^2} \tag{14}$$

Reynolds number of the flow relative to the first-stage rotor blades at the mean radius was then calculated by combining the results from equations (11) and (14) in the expression

$$Re = \frac{c\rho_3 V_{3,r}}{\mu_3} \tag{15}$$

REFERENCE

1. Sinnette, John T., Jr., Schey, Oscar W., and King, J. Austin: Performance of NACA Eight-Stage Axial-Flow Compressor Designed on the Basis of Airfoil Theory. NACA Rep. 758, 1943.

2. Jacobs, Eastman N., and Sherman, Albert: Airfoil Section Characteristics as Affected by Variations of the Reynolds Number. NACA Rep. 586, 1937.

TABLE I - RANGE OF INVESTIGATION

Compressor Mach number	Compressor-inlet Reynolds number	Compressor-inlet total temperature (°R)	Compressor-inlet total pressure (lb/sq ft)	Pressure altitude (ft)
0.89	205,400	507	805	25,100
	132,400	507	511	35,100
	83,700	504	316	45,100
	66,700	507	249	50,200
0.82	219,500	603	1138	17,000
	218,200	464	808	25,100
0.76	208,500	608	1143	16,800
	207,300	464	807	25,100
0.70	197,000	604	1149	16,700
	197,000	458	806	25,100
0.82	142,700	599	722	27,700
	141,000	458	512	35,100
0.76	133,600	604	727	27,500
	131,400	458	512	35,100
0.70	124,600	606	730	27,300
	124,900	458	512	35,100
0.82	87,500	601	447	37,900
	87,500	459	318	45,100
0.76	82,200	607	450	37,700
	83,700	458	318	45,100
0.70	77,500	606	454	37,500
	77,500	459	317	45,100
0.82	69,300	598	352	42,900
	68,300	462	247	50,400
0.76	64,900	607	355	42,700
	65,500	458	247	50,400
0.70	61,900	602	356	42,700
	60,300	459	247	50,400

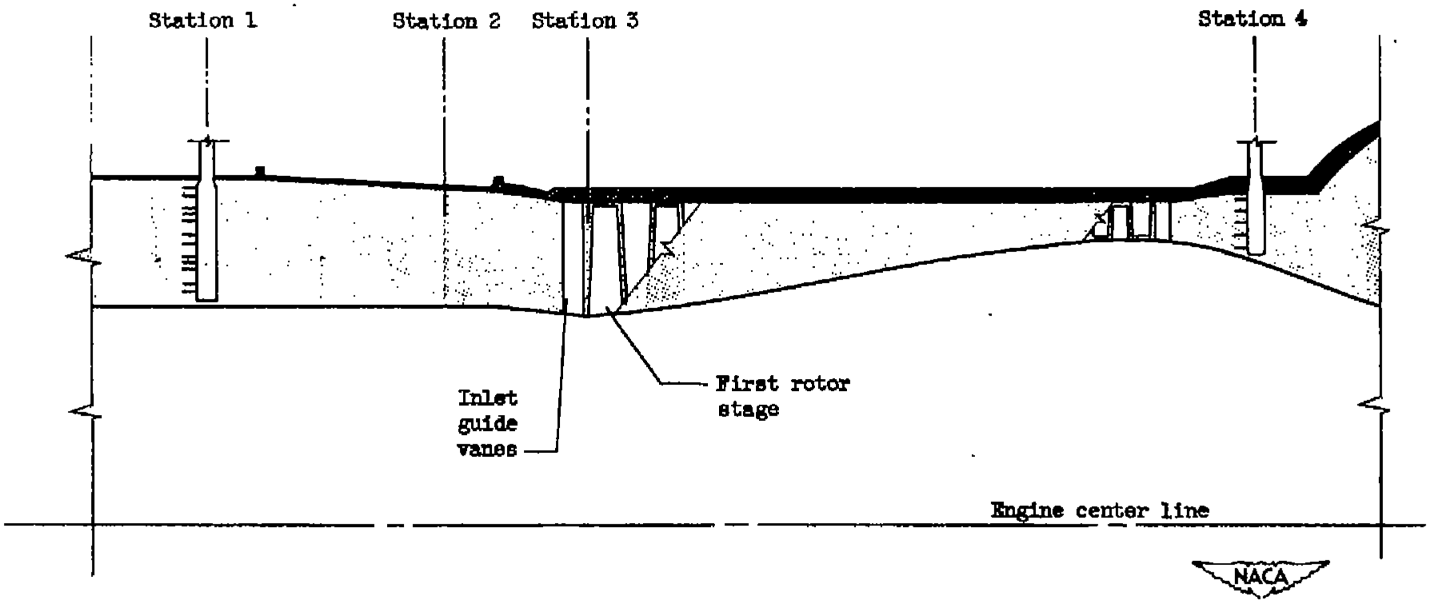
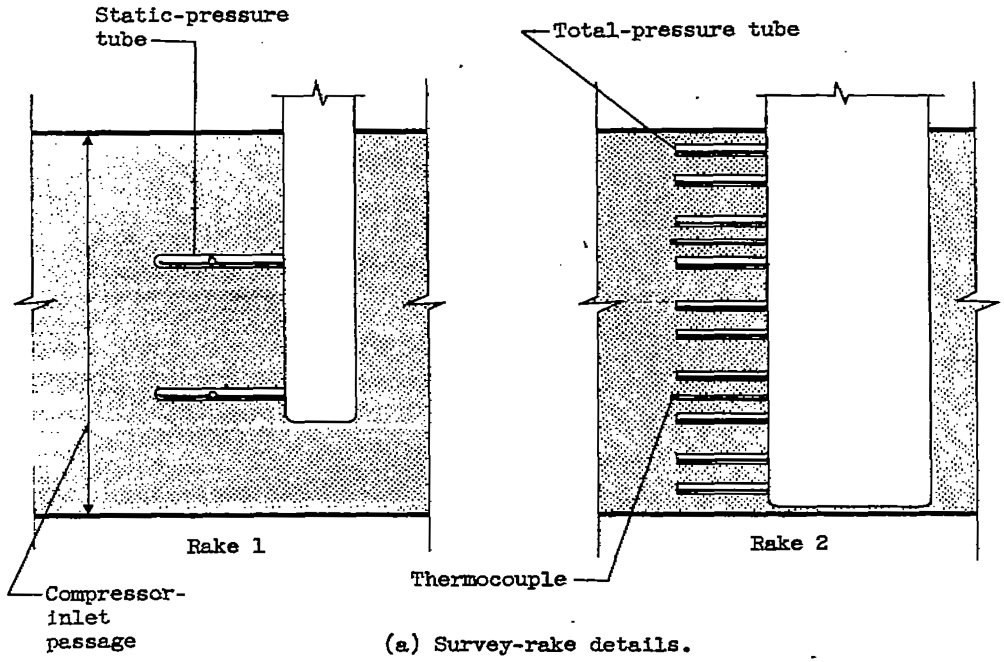
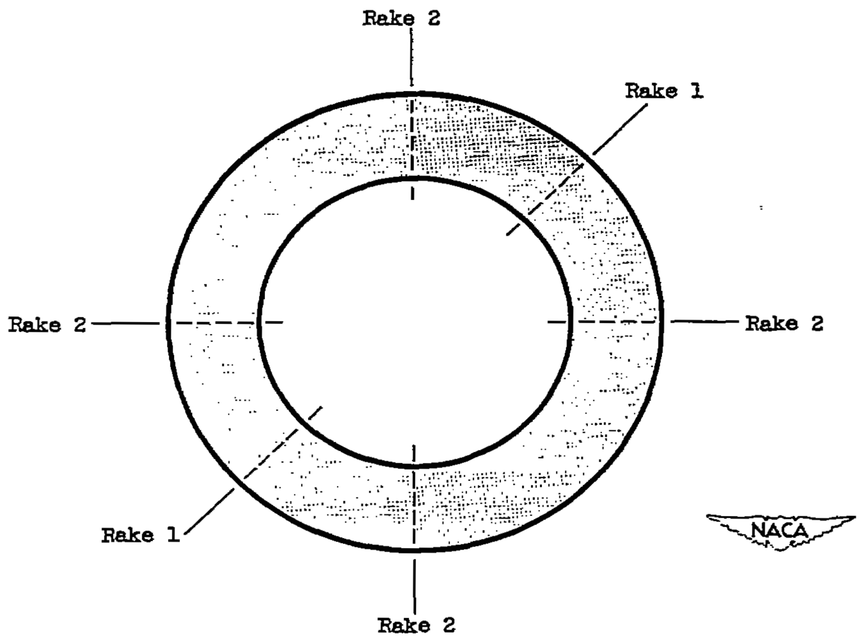


Figure 1. - Schematic view of compressor showing measuring stations.



(a) Survey-rake details.



(b) Location of survey rakes.

Figure 2. - Location and details of instrumentation installed at engine inlet, station 1.

1161

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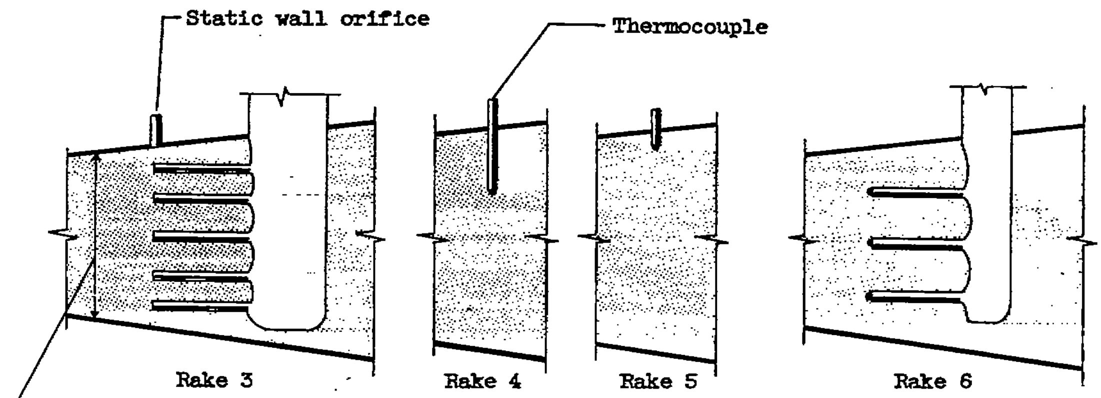
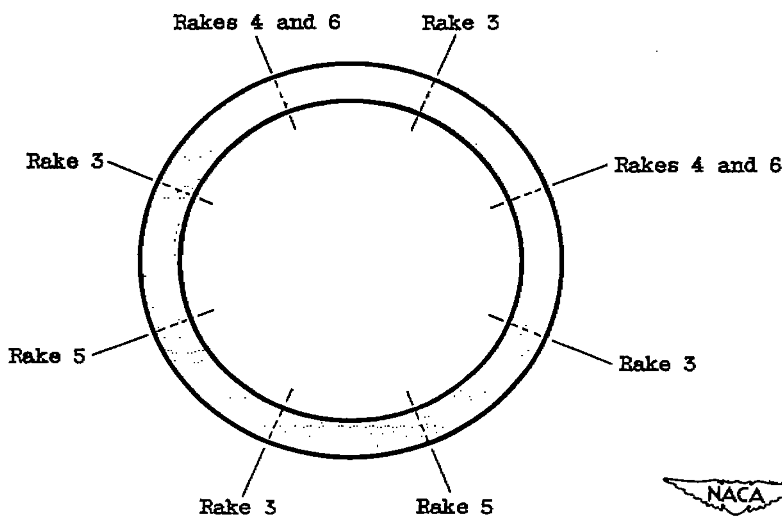


(a) Survey-rake details.



(b) Location of survey rakes.

Figure 3. - Location and details of instrumentation installed at compressor outlet, station 4.

1161

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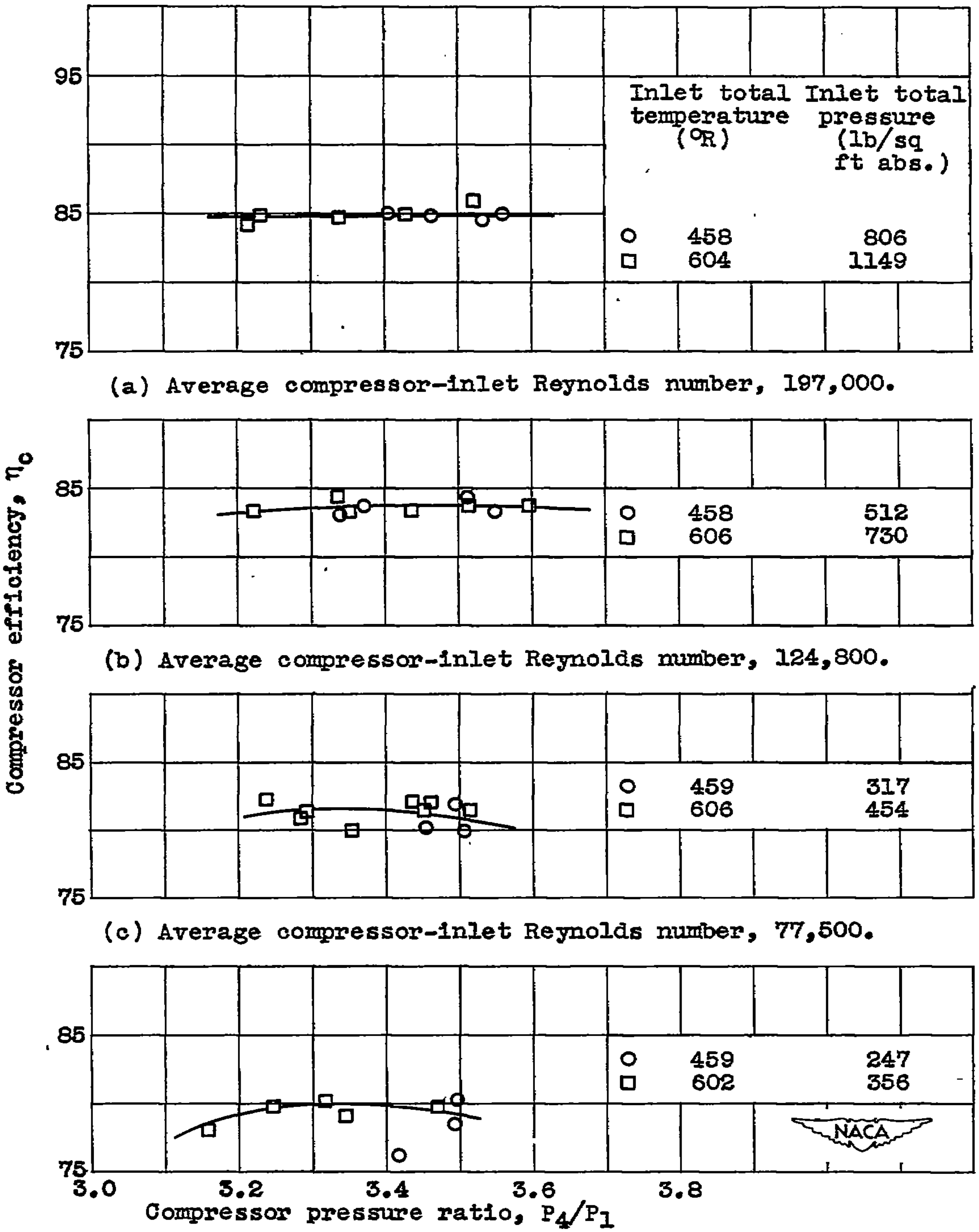


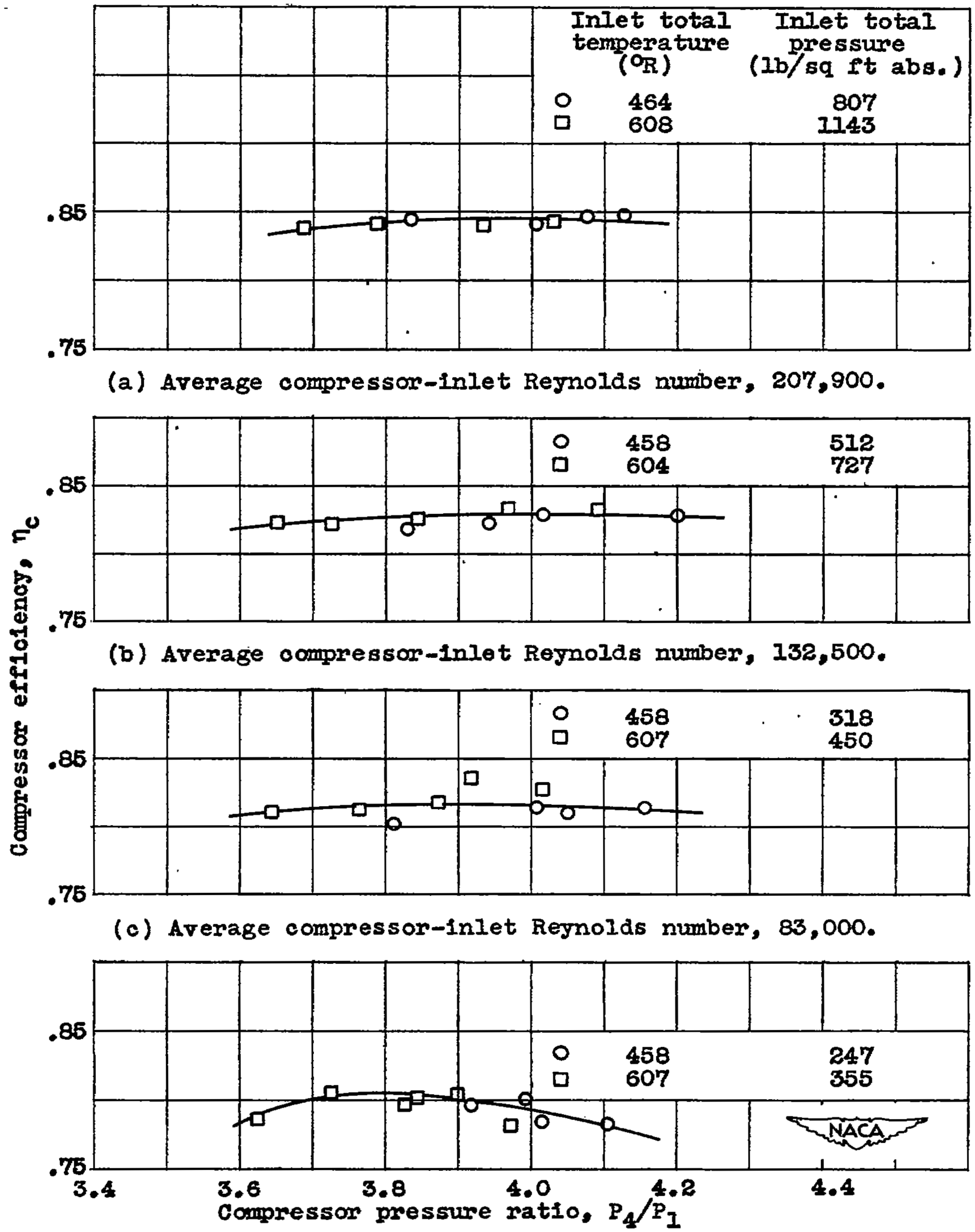
(a) Average compressor-inlet Reynolds number, 197,000.

(b) Average compressor-inlet Reynolds number, 124,800.

(c) Average compressor-inlet Reynolds number, 77,500.

(d) Average compressor-inlet Reynolds number, 61,100.

Figure 4. - Variation of compressor efficiency with compressor pressure ratio at compressor Mach number of 0.70.

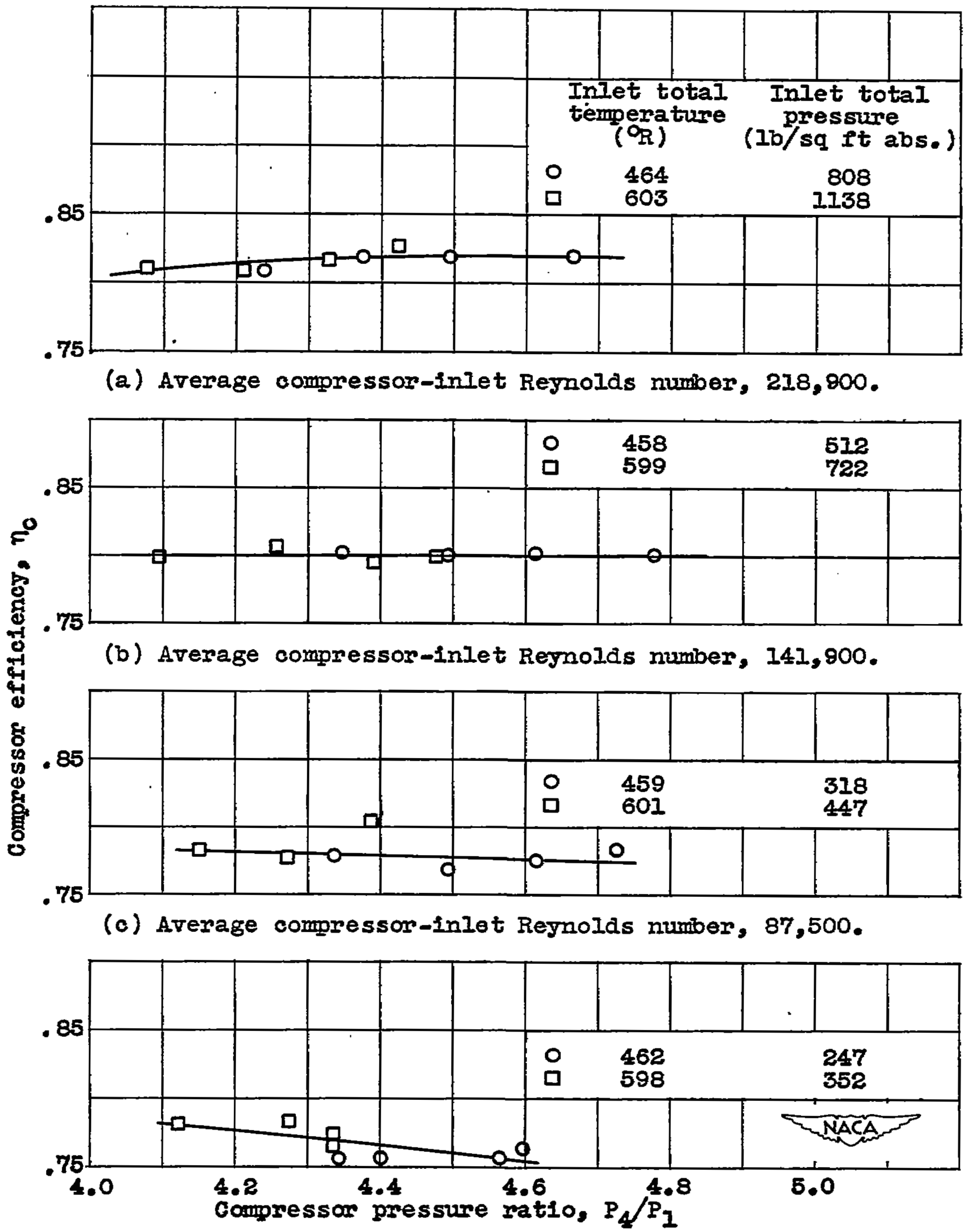


(d) Average compressor-inlet Reynolds number, 65,200.

Figure 5. - Variation of compressor efficiency with compressor pressure ratio at compressor Mach number of 0.76.

1911

1161



(a) Average compressor-inlet Reynolds number, 218,900.

(b) Average compressor-inlet Reynolds number, 141,900.

(c) Average compressor-inlet Reynolds number, 87,500.

(d) Average compressor-inlet Reynolds number, 68,800.

Figure 6. - Variation of compressor efficiency with compressor pressure ratio at compressor Mach number of 0.82.

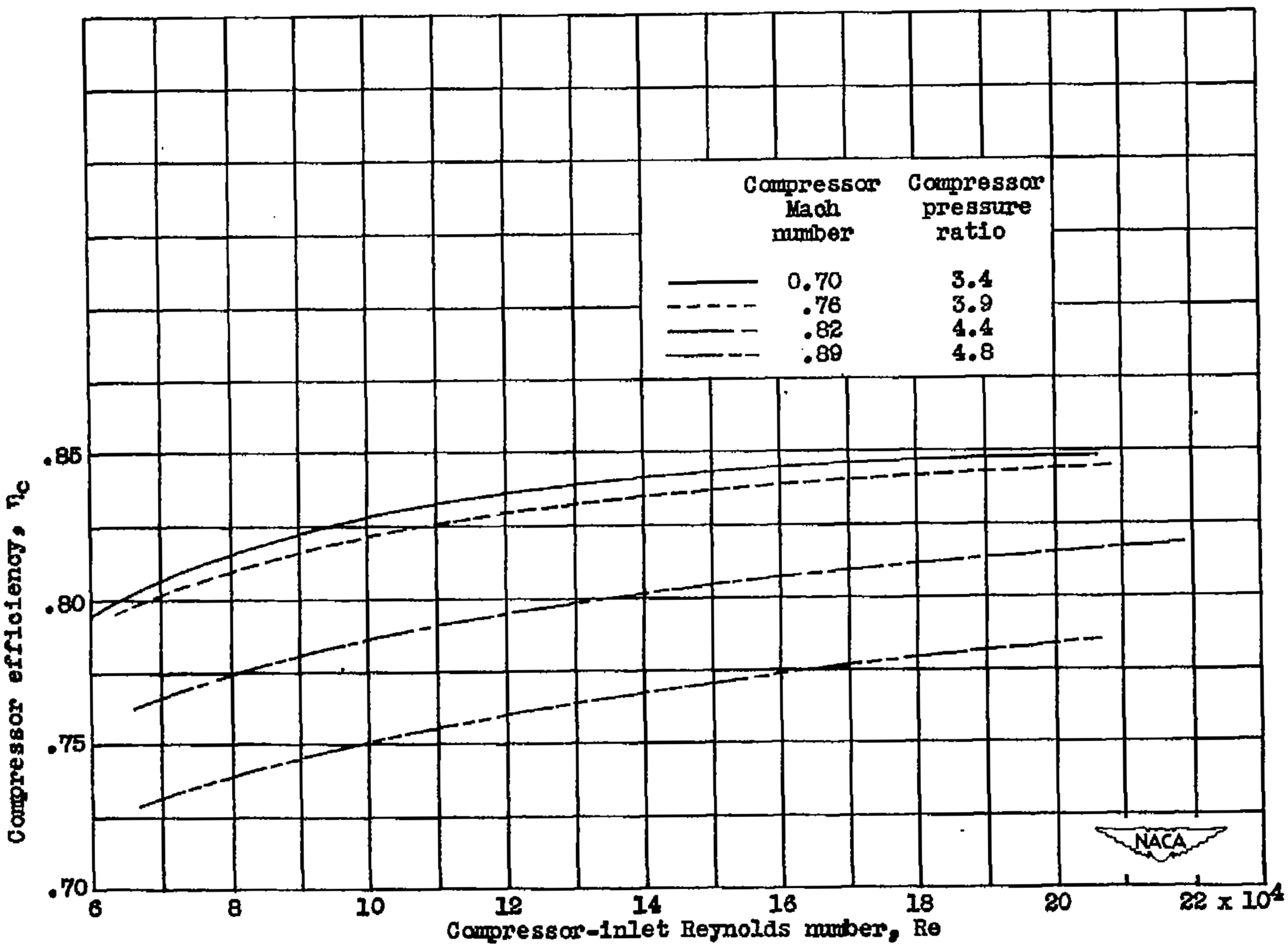


Figure 7. - Effect of compressor-inlet Reynolds number on compressor efficiency.

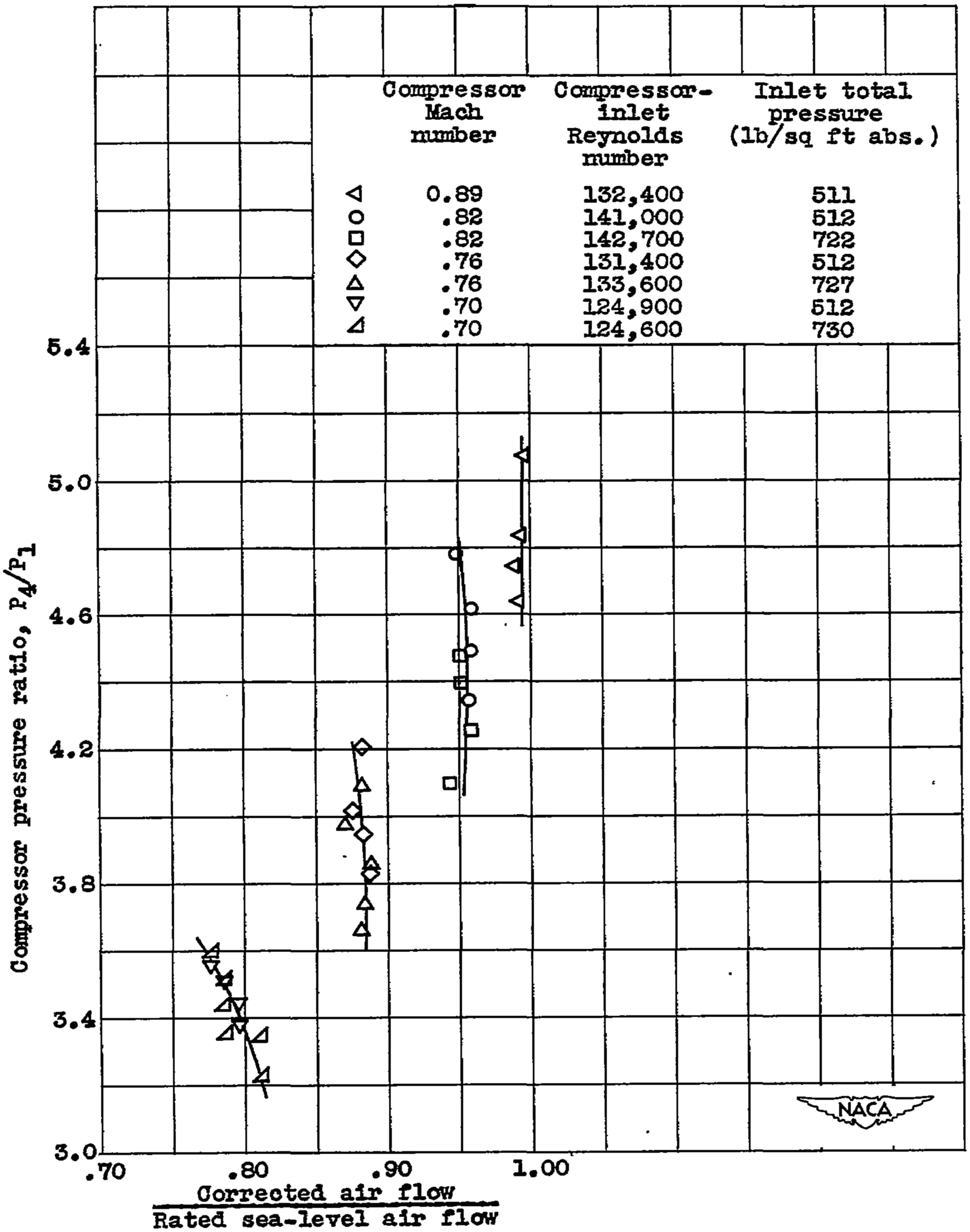


Figure 8. - Variation of compressor pressure ratio with fraction of rated sea-level air flow for constant values of compressor Mach number and compressor-inlet Reynolds number.

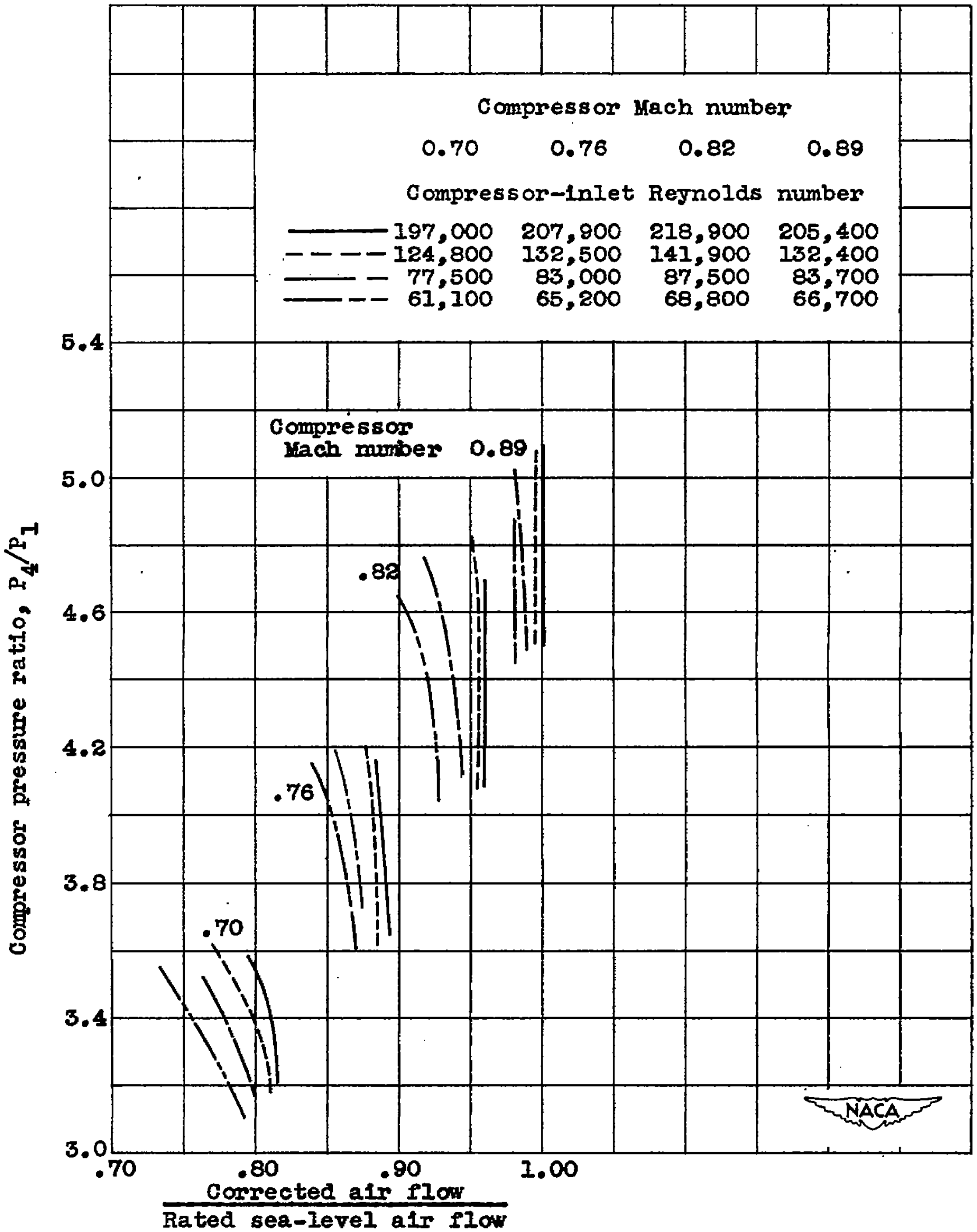


Figure 9. - Effect of compressor-inlet Reynolds number on relation between compressor pressure ratio and fraction of rated sea-level air flow.

1161

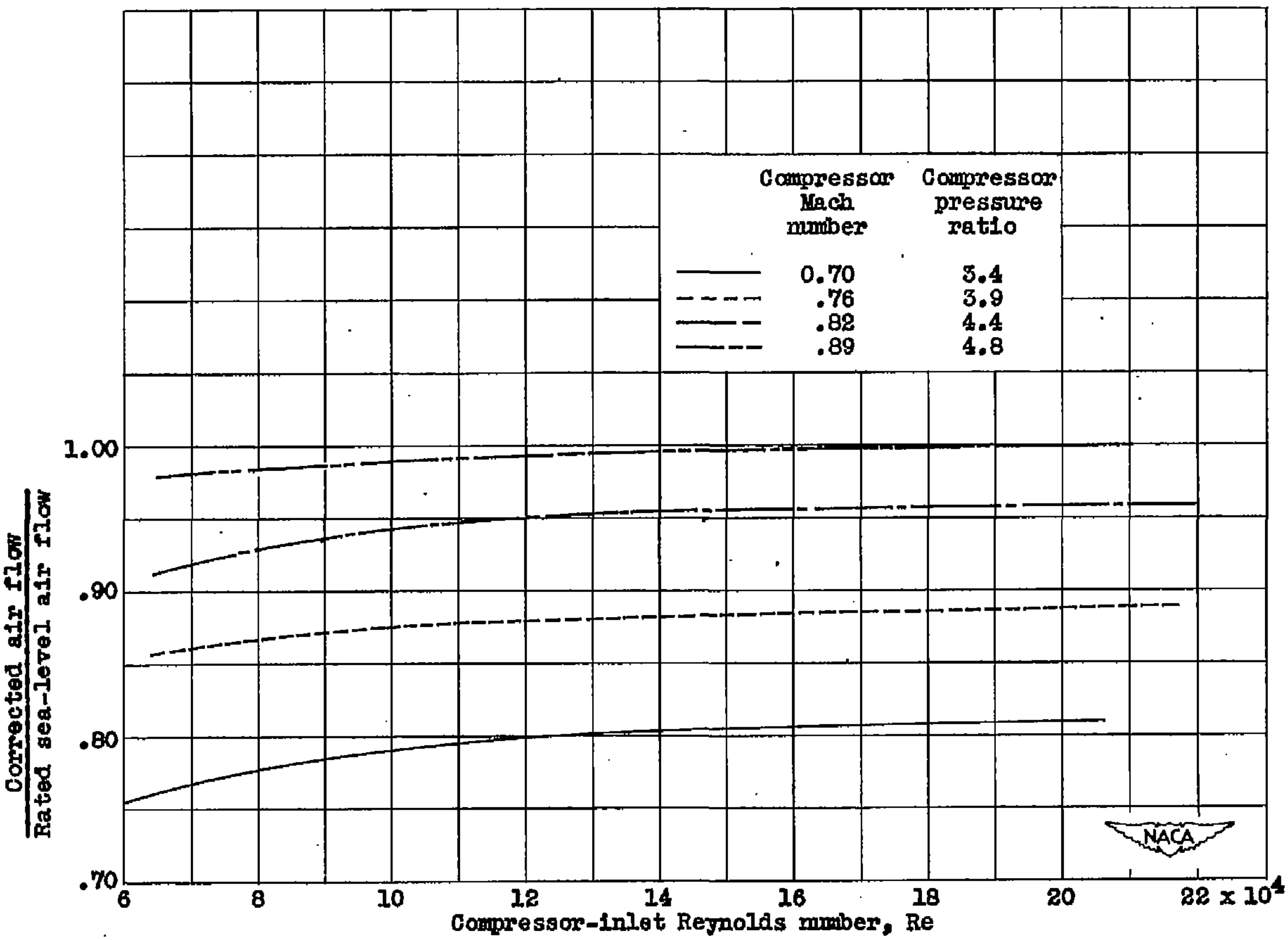


Figure 10. - Effect of compressor-inlet Reynolds number on fraction of rated sea-level air flow.

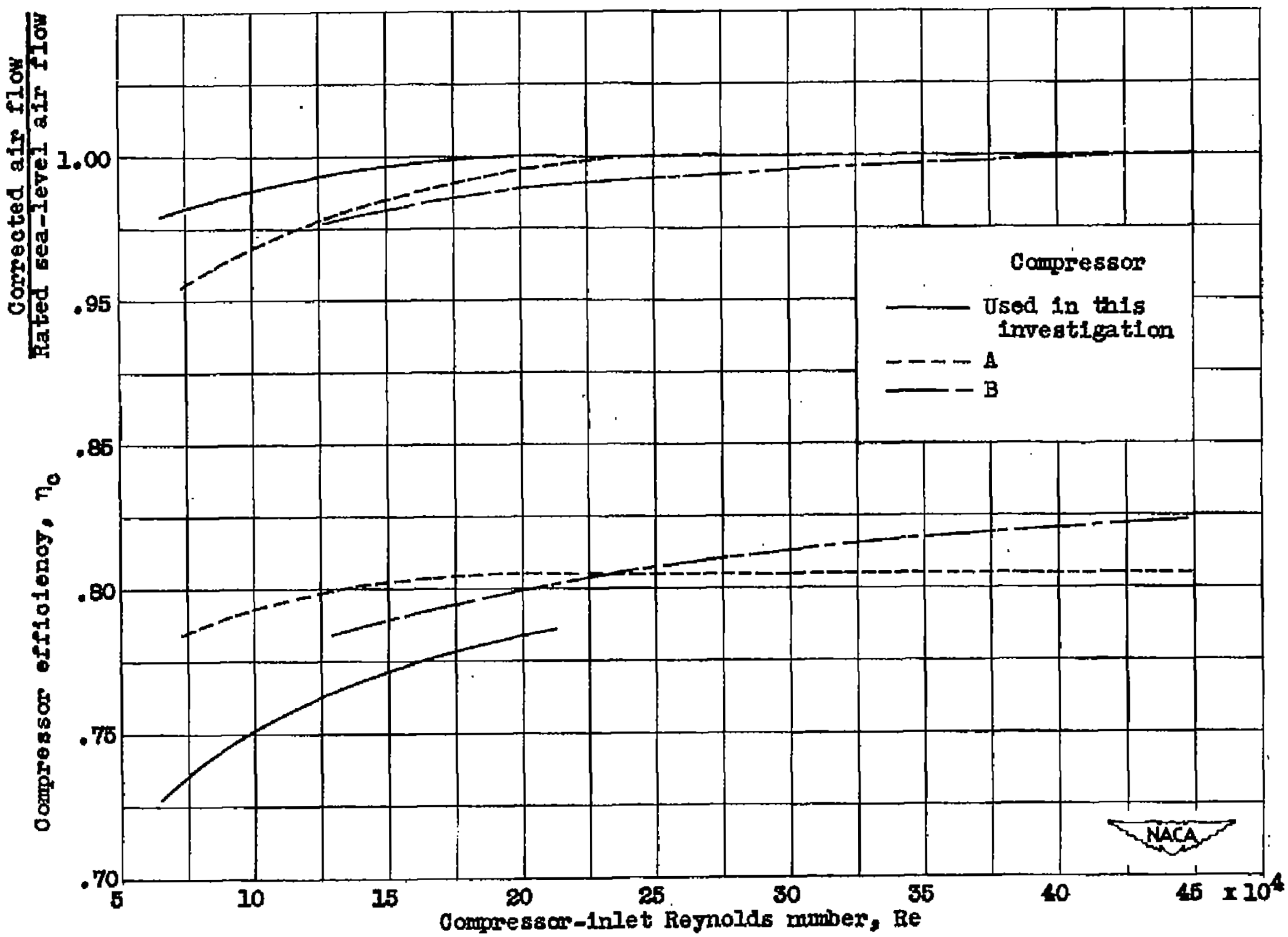


Figure 11. - Comparison of Reynolds number effect at rated Mach number on performance of compressor studied in this investigation and compressors of two other current turbojet engines.

1911